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REGULAR ARTICLES

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## $\alpha_2$ -Macroglobulin as a $\beta$ -Amyloid Peptide-Binding Plasma Protein

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**Abstract:** The  $\beta$ -amyloid peptide (A $\beta$ ) is a normal proteolytic processing product of the amyloid precursor protein, which is constitutively expressed by many, if not most, cells. For reasons that are still unclear, A $\beta$  is deposited in an aggregated fibrillar form in both diffuse and senile plaques in the brains of patients with Alzheimer's disease (AD). The factor(s) responsible for the clearance of soluble A $\beta$  from biological fluids or tissues are poorly understood. We now report that human  $\alpha_2$ -macroglobulin ( $\alpha_2$ M), a major circulating endoprotease inhibitor, which has recently been shown to be present in senile plaques in AD, binds  $^{125}$ I-A $\beta_{(1-42)}$  with high affinity (apparent dissociation constant of  $3.8 \times 10^{-10}$  M). Approximately 1 mol of A $\beta$  is bound per mole of  $\alpha_2$ M. Both native and methylamine-activated  $\alpha_2$ M bind  $^{125}$ I-A $\beta_{(1-42)}$ . The binding of  $^{125}$ I-A $\beta_{(1-42)}$  to  $\alpha_2$ M is enhanced by micromolar concentrations of Zn $^{2+}$  (but not Ca $^{2+}$ ) and is inhibited by noniodinated A $\beta_{(1-42)}$  and A $\beta_{(1-40)}$  but not by the reverse peptide A $\beta_{(40-1)}$  or the cytokines interleukin 1 $\beta$  or interleukin 2.  $\alpha_1$ -Antichymotrypsin, another plaque-associated protein, inhibits both the binding of  $^{125}$ I-A $\beta_{(1-42)}$  to  $\alpha_2$ M as well as the degradation of  $^{125}$ I-A $\beta_{(1-42)}$  by proteinase-activated  $\alpha_2$ M. Moreover, the binding of  $^{125}$ I-A $\beta_{(1-42)}$  to  $\alpha_2$ M protects the peptide from proteolysis by exogenous trypsin. These data suggest that  $\alpha_2$ M may function as a carrier protein for A $\beta$  and could serve to either facilitate or impede clearance of A $\beta$  from tissues such as the brain.

**Key Words:**  $\beta$ -Amyloid peptide—Amyloid precursor protein—Alzheimer's disease—Senile plaques— $\alpha_2$ -Macroglobulin—Brain.

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back et al., 1962). In addition to binding and capturing proteinases,  $\alpha_2$ M also binds a number of polypeptide growth factors and cytokines (James, 1990; Borth, 1992). Although the exact physiological significance of the binding of these peptides or cytokines to  $\alpha_2$ M is uncertain, it has been shown that such binding protects smaller peptide substrates from proteolytic degradation (Legrés et al., 1995). Furthermore, the clearance and catabolism of these peptides or cytokines may be enhanced after the Ca $^{2+}$ -dependent binding and endocytosis of  $\alpha_2$ M via its well-described receptor, the  $\alpha_2$ M receptor/low-density lipoprotein receptor-related protein (LRP) (Moestrup et al., 1990). Thus,  $\alpha_2$ M may serve as a humoral or tissue binding or carrier protein for targeting peptides to their sites of action or clearing them from tissues.

Increased deposition of amyloid is one of the principal neuropathological features of Alzheimer's disease (AD) (Selkoe, 1994). Amyloid deposits are composed primarily of a 39–43-amino-acid peptide(s), the  $\beta$ -amyloid peptide (A $\beta$ ), which is a proteolytic processing product(s) of a larger integral transmembrane protein, the amyloid precursor protein (APP) (Kang et al., 1987). The A $\beta$  peptide(s), once formed, can oligomerize and aggregate into insoluble fibrils that are directly toxic to neurons (Pike et al., 1991). Overproduction of A $\beta$  after overexpression of a mutant APP transgene in mice results in amyloid deposition and neurodegeneration that is reminiscent of that seen in

$\alpha_2$ -Macroglobulin ( $\alpha_2$ M), present in high concentrations in human plasma, is a 720-kDa glycoprotein consisting of four identical (180-kDa) subunits (Sottrup-Jensen, 1989).  $\alpha_2$ M has been shown to subserve a unique trapping mechanism both in vitro and in vivo, irreversibly capturing a variety of proteinases, resulting in "pan-proteinase" inhibitory activity, especially for large protein substrates (Ganrot, 1966; Barrett and Starkey, 1973). By contrast, proteinase-activated  $\alpha_2$ M is able to efficiently degrade smaller substrates (Haver-

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**Abbreviations used:** A $\beta$ ,  $\beta$ -amyloid peptide; AD, Alzheimer's disease; APP, amyloid precursor protein; BAPNA, sodium benzoyl-DL-arginine-*p*-nitroanilide; BSA, bovine serum albumin; IL, interleukin; LRP, low-density lipoprotein receptor-related protein;  $\alpha_2$ M,  $\alpha_2$ -macroglobulin;  $\alpha_2$ M-MA, methylamine-activated  $\alpha_2$ M;  $\alpha_2$ M-T, trypsin-activated  $\alpha_2$ M; PBS, phosphate-buffered saline; SDS-PAGE, sodium dodecyl sulfate-polyacrylamide gel electrophoresis.

AD (Games et al., 1995). However, overproduction of A $\beta$  (due to either increased expression of APP or processing to A $\beta$ ) does not appear to occur in the vast majority of patients with AD, suggesting that differences in either the metabolism or clearance of A $\beta$ , or both, may underlie the deposition of amyloid which invariably occurs in AD (Van Gool et al., 1995).

In addition to amyloid, other proteinaceous constituents of senile plaques have been identified. One of these,  $\alpha_2$ M, is up-regulated in AD brain where it has been localized to neuritic but not diffuse (preamyloid) plaques (Strauss et al., 1992; Van Gool et al., 1993). Moreover, the  $\alpha_2$ M receptor or LRP is also expressed in brain (in both neurons and glia) and is especially abundant in areas such as the hippocampus and entorhinal cortex, which are selectively affected in AD (Rebeck et al., 1993; Tooyama et al., 1993). In light of the well-described capacity of  $\alpha_2$ M to bind various peptides and cytokines, as well as its postulated role in the pathogenesis of AD (Strauss, et al., 1992; Van Gool et al., 1993), we examined the binding of A $\beta$  to  $\alpha_2$ M.

## MATERIALS AND METHODS

### Materials

Synthesized human A $\beta_{(1-42)}$  was purchased from Bachem (Torrance, CA, U.S.A.). Human  $\alpha_2$ M was purchased from Calbiochem (La Jolla, CA, U.S.A.). Methylamine, sodium benzoyl-DL-arginine-*p*-nitroanilide (BAPNA),  $\alpha_1$ -antichymotrypsin, anti- $\alpha_2$ M antiserum, porcine chymotrypsin, and trypsin were from Sigma (St. Louis, MO, U.S.A.). Microcon microconcentrators were from Amicon (Beverly, MA, U.S.A.).

### Iodination of A $\beta_{(1-42)}$

A $\beta_{(1-42)}$  was radiolabeled with Na<sup>125</sup>I according to the chloramine T-labeling method of Du Pont Medical Products (Boston, MA, U.S.A.) (sp. act. 2,200 Ci/mmol) (Banks et al., 1991). In brief, A $\beta_{(1-42)}$  peptide was incubated with Na<sup>125</sup>I and chloramine T in phosphate-buffered saline (PBS), pH 7.5, for 2 min. The reaction was quenched by the addition of sodium metabisulfite and purified by HPLC (99% purity). <sup>125</sup>I-A $\beta_{(1-42)}$  was stored in PBS/0.1% bovine serum albumin (BSA) at -80°C or -20°C for <2 months. The quality of <sup>125</sup>I-A $\beta_{(1-42)}$  was determined by native or sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE).

### Activation of $\alpha_2$ M with methylamine or trypsin

Human  $\alpha_2$ M was incubated at room temperature with 0.23 M methylamine for 110 min to yield methylamine-activated  $\alpha_2$ M ( $\alpha_2$ M-MA), or with a 4:1 molar excess of trypsin for 30 min to yield trypsin-activated  $\alpha_2$ M ( $\alpha_2$ M-T). All incubations were performed in a buffer consisting of 0.2 M HEPES (pH 8.0), 50 mM NaCl, and 2 mM EDTA. Excess methylamine, trypsin, or chymotrypsin was removed by membrane ultrafiltration (Bonner et al., 1992).

### Binding of <sup>125</sup>I-A $\beta_{(1-42)}$ to $\alpha_2$ M

$\alpha_2$ M (10–400  $\mu$ g/assay) was incubated with 0.2–1.0 ng <sup>125</sup>I-A $\beta_{(1-42)}$  in PBS containing 0.2% Triton X-100 at 37°C for 2 h in a total incubation volume of 40  $\mu$ l for gel electro-

phoresis analysis or 200  $\mu$ l for immunoprecipitation experiments.

### Gel electrophoresis

Electrophoresis of the <sup>125</sup>I-A $\beta$ / $\alpha_2$ M complex in a native gel (5% Tris-borate) was performed as previously described (Nelles et al., 1980). Samples were electrophoresed using 10% PAGE for 2–3 h at 150–200 V, subsequently stained with Coomassie Brilliant Blue, and dried before autoradiography. To quantify the radioactivity of the complex, the stained bands of interest were removed with a razor blade and counted in a  $\gamma$ -scintillation counter.

### Trypsin binding assay for $\alpha_2$ M

The purity of native  $\alpha_2$ M was tested by the assay of Ganrot (1966). Both  $\alpha_2$ M and  $\alpha_2$ M-MA were tested for trypsin binding activity by a previously described method (Bonner et al., 1992). Increasing concentrations (50  $\mu$ l/well) of  $\alpha_2$ M in 25 mM Tris-HCl, 150 mM NaCl, pH 7.4, were incubated with 3  $\mu$ l/well of 1 mg/ml trypsin for 10 min and then 6  $\mu$ l/well of 1 mg/ml soybean trypsin inhibitor was added. After 10 min, 80  $\mu$ l of 0.1 M Tris-HCl, 10 mM CaCl<sub>2</sub> buffer, pH 8.0, was added, followed by 100  $\mu$ l/well 3 mM BAPNA. The reaction was stopped by the addition of 10  $\mu$ l of glacial acetate and read at 405 nm.

### Immunoprecipitation experiments

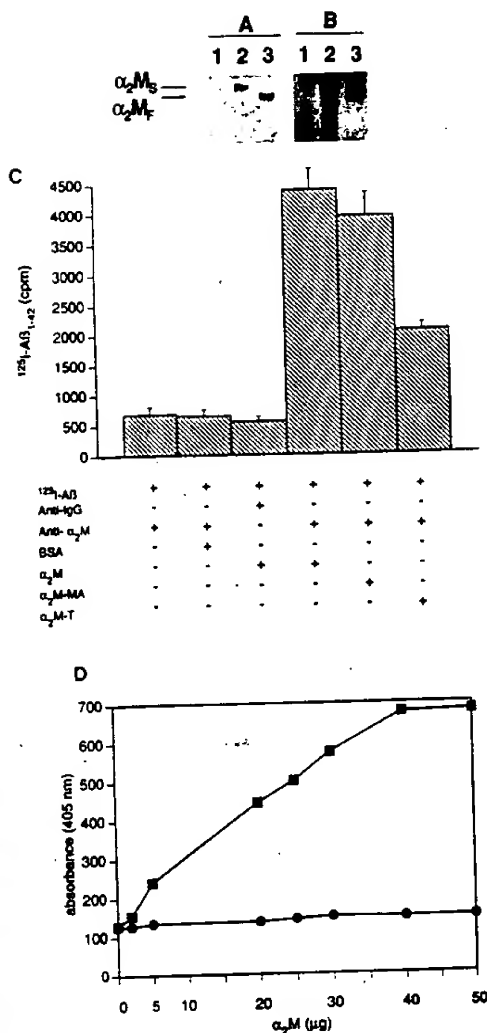
The <sup>125</sup>I-A $\beta$ / $\alpha_2$ M reaction mixture (200  $\mu$ l) was incubated with 20  $\mu$ l of anti- $\alpha_2$ M antiserum (or control serum) at 4°C overnight. Immunoprecipitates were centrifuged at 10,000 g and washed five times with binding buffer before scintillation counting.

### Separation of <sup>125</sup>I-A $\beta_{(1-42)}$ and $\alpha_2$ M using HPLC

The binding of <sup>125</sup>I-A $\beta_{(1-42)}$  and purified  $\alpha_2$ M or  $\alpha_2$ M present in human serum was analyzed by HPLC gel-filtration chromatography using a modification of the method of Ikai et al. (1988). The equipment consisted of a TSK-Gel G4000PWXL column (7.8 mm i.d.  $\times$  30 mm; Tosoh, Montgomeryville, PA, U.S.A.) and a Beckman System Gold Chromatograph with in-line UV detection (Beckman Instruments, San Ramon, CA, U.S.A.). After incubation at 37°C for 2 h, the sample was filtered by microconcentration with a 300-kDa filter to remove free <sup>125</sup>I-A $\beta_{(1-42)}$ . The recovered <sup>125</sup>I-A $\beta$ / $\alpha_2$ M complex was dissolved in PBS, then isocratically eluted in a mobile phase containing 150 mM NaCl and 50 mM NaH<sub>2</sub>PO<sub>4</sub>, pH 6.8.  $\alpha_2$ M was quantified by absorbance at 280 nm. <sup>125</sup>I-A $\beta_{(1-42)}$  content was determined by measurement of radioactivity in sequentially collected fractions. To measure binding of <sup>125</sup>I-A $\beta_{(1-42)}$  to  $\alpha_2$ M present in human serum, the fraction corresponding to  $\alpha_2$ M was collected as described above and then filtered to remove albumin and other smaller proteins. The A $\beta$ / $\alpha_2$ M complex recovered was then rechromatographed in the same manner as for purified  $\alpha_2$ M.

### Effect of trypsin on the <sup>125</sup>I-A $\beta$ / $\alpha_2$ M-MA complex

$\alpha_2$ M-MA (40  $\mu$ g) was incubated with <sup>125</sup>I-A $\beta_{(1-42)}$  for 2 h at 37°C in the same binding buffer as described above. The resulting sample was then treated with various concentrations of trypsin for 1 h at 37°C and the amount of bound <sup>125</sup>I-A $\beta_{(1-42)}$  analyzed by using a native 5% gel or by immunoprecipitation as described above. Control incubations were performed in an identical fashion in the absence of  $\alpha_2$ M-MA or with control antiserum.



**FIG. 1.** The binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$ . Human  $\alpha_2\text{M}$  (1 mg/ml) was incubated with  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  (5 ng/ml) and the bound peptide/ $\alpha_2\text{M}$  measured as described under Materials and Methods. **A** (Coomassie Blue staining) and **B** (autoradiogram of a typical gel): Lane 1 corresponds to  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  alone. Lanes 2 and 3 show that  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binds to native  $\alpha_2\text{M}$  (slow form) and to  $\alpha_2\text{M-MA}$  (fast form). **C**: Immunoprecipitation of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}/\alpha_2\text{M}$  complex with rabbit anti- $\alpha_2\text{M}$  antiserum. Human- $\alpha_2\text{M}$  (1 mg/ml) was incubated with  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  (5 ng/ml). The amount of immunoprecipitable  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  was reduced by  $\geq 60\%$  when incubated with  $\alpha_2\text{M-T}$  compared with native  $\alpha_2\text{M}$  or  $\alpha_2\text{M-MA}$ . Background precipitation was  $< 15\%$  of control. Each experiment was repeated three times with similar results. **D**: Trypsin binding assay for  $\alpha_2\text{M}$ . Native  $\alpha_2\text{M}$  (■) possesses trypsin binding activity, whereas  $\alpha_2\text{M-MA}$  (●) does not bind trypsin.

## RESULTS

Using native gel electrophoresis, we observed binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to purified human  $\alpha_2\text{M}$ . As shown in Fig. 1, under our incubation conditions,  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binds to native  $\alpha_2\text{M}$  and  $\alpha_2\text{M-MA}$  (Fig. 1B, lanes 2 and 3). To further characterize the binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$ , rabbit anti-human  $\alpha_2\text{M}$  polyclonal antiserum was used to immunoprecipitate the  $^{125}\text{I}$ -

$\text{A}\beta_{(1-42)}/\alpha_2\text{M}$  binding complex. From Fig. 1B it is clear that a significant amount of radioactivity can be immunoprecipitated by using an antiserum to human  $\alpha_2\text{M}$ . However, only background radioactivity is precipitated with an antiserum to human IgG or when BSA is substituted for  $\alpha_2\text{M}$ . Similar to the data using native gel electrophoresis to separate bound from free  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$ , it appears that  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binds to native  $\alpha_2\text{M}$  and  $\alpha_2\text{M-MA}$ , whereas less binding to  $\alpha_2\text{M-T}$  is observed (Fig. 1C). For convenience, we used  $\alpha_2\text{M-MA}$  for most of the subsequent experiments. To confirm that native  $\alpha_2\text{M}$  was of good quality and had been completely converted to activated  $\alpha_2\text{M}$  after treatment with methylamine, the trypsin binding assay for  $\alpha_2\text{M}$  was also used (Bonner et al., 1992). The data demonstrated that  $> 90\%$  of native  $\alpha_2\text{M}$  in selected lots possessed good trypsin binding activity that is proportional to the increasing amount of slow  $\alpha_2\text{M}$ , but methylamine treatment inhibited this binding capacity (Fig. 1D).

To characterize the specificity of  $\text{A}\beta$  binding to  $\alpha_2\text{M}$ , competition experiments designed to examine the effects of various peptides and cytokines on the binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M-MA}$  were performed. Binding was examined in the presence of a  $10^3$ -fold molar excess of unlabeled  $\text{A}\beta_{(1-42)}$  (Fig. 2),  $\text{A}\beta_{(1-40)}$  or  $\text{A}\beta_{(40-1)}$  (data not shown), or a  $\sim 3,000$ -fold molar excess of interleukin  $1\beta$  (IL- $1\beta$ ) or interleukin 2 (IL-2) (data not shown). The binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M-MA}$  is observed in the absence of unlabeled  $\text{A}\beta_{(1-42)}$ , but is completely inhibited by concentrations of  $\text{A}\beta_{(1-42)} \geq 1.1 \mu\text{M}$  ( $\geq 44 \text{ pmol/assay}$ ) (Fig. 2). Moreover,  $\text{A}\beta_{(1-40)}$ , not  $\text{A}\beta_{(40-1)}$  can also effectively inhibit the binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$ . Finally, little to no inhibition of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binding to  $\alpha_2\text{M}$  is observed with high concentrations of IL- $1\beta$  or IL-2, two cytokines that have been previously shown to bind to  $\alpha_2\text{M}$  (Borth and Luger, 1989; Légrés et al., 1995).

The binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to various concentrations of  $\alpha_2\text{M}$  was further investigated by using immunoprecipitation. The binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$  increases with increasing concentrations of  $\alpha_2\text{M}$ , such that saturation of binding [0.2 ng  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  (0.05 pmol)] is reached at 200  $\mu\text{g}$   $\alpha_2\text{M}$  (276 pmol) (Fig. 3). To determine the time required for  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binding to  $\alpha_2\text{M}$  to reach equilibrium, binding was performed at pH 7.4 [0.2 ng  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  (0.05 pmol) and 40  $\mu\text{g}$   $\alpha_2\text{M}$  (55 pmol)] and the amount of binding was determined at various time points (0.5–24 h) by

**FIG. 2.** Competition experiments. Competition studies were conducted at a constant ratio of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}/\alpha_2\text{M-MA}$  [5 ng/ml (1 nM)/1 mg/ml (1.4  $\mu\text{M}$ )]. The binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M-MA}$  was performed in the absence (1) or presence (2) of 5  $\mu\text{g}/\text{ml}$  (1  $\mu\text{M}$ ) of unlabeled  $\text{A}\beta_{(1-42)}$ . These competition experiments were repeated twice with similar results.

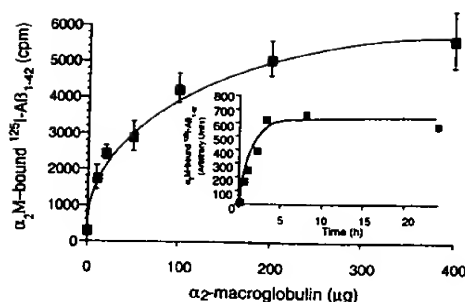


FIG. 3. Concentration- and time-dependent binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$ .  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  (5 ng/ml) was incubated with various amounts of  $\alpha_2\text{M}$  at  $37^\circ\text{C}$  for 2 h. The complex was immunoprecipitated by incubation with anti- $\alpha_2\text{M}$  antiserum. The amount of radioactivity of the  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}/\alpha_2\text{M}$  complex was determined by scintillation counting. Inset: Time course of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binding to  $\alpha_2\text{M}$ .  $\alpha_2\text{M}$  (1 mg/ml) was incubated with  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  (5 ng/ml) for various times (0.5–24 h) at  $37^\circ\text{C}$  in 40  $\mu\text{l}$  of the binding buffer, pH 7.4. Bound from free  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  was separated by gel electrophoresis (see text for details). The amount of radioactivity was determined by direct scintillation counting of the excised bands.

using native gel electrophoresis as described above (see inset). The results indicate that  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binds to  $\alpha_2\text{M}$  with a  $t_{1/2}$  of  $\sim 90$  min and equilibrium is reached at  $\sim 4$  h. Using 40  $\mu\text{g}$   $\alpha_2\text{M}$  (55 pmol)/assay, we varied the concentration of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  and separated bound from free radioligand by native gel electrophoresis. A saturation isotherm of "specific" binding is shown in Fig. 4. The apparent dissociation constant and maximal binding capacity for  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binding to  $\alpha_2\text{M}$  were estimated by Scatchard analysis (Fig. 4, inset), yielding an apparent dissociation constant ( $K_D$ ) of  $\sim 3.8 \times 10^{-10}$  M and an apparent  $B_{\text{max}}$  of  $\sim 1.1$  binding sites of  $\text{A}\beta/\text{mol}$  of  $\alpha_2\text{M}$ .

To explore incubation conditions and cofactors that

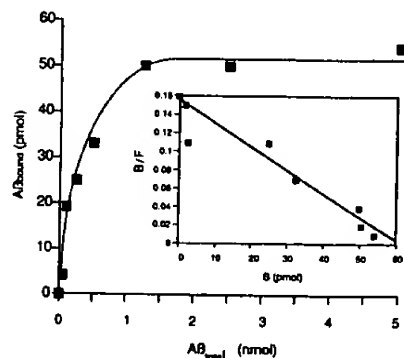


FIG. 4. Saturation isotherm and Scatchard analysis of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binding to  $\alpha_2\text{M}$ .  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  (5 ng/ml) with or without cold  $\text{A}\beta_{(1-42)}$  (0.1–5 nM) was incubated with native human  $\alpha_2\text{M}$  (1 mg/ml) for 4 h as described in the text. Bound from free radioligand was determined by nondenaturing gel electrophoresis as described in the text. Scatchard analysis of the binding data (inset) yielded an apparent dissociation constant of  $3.8 \times 10^{-10}$  M. Data are from a representative experiment repeated twice with similar results.

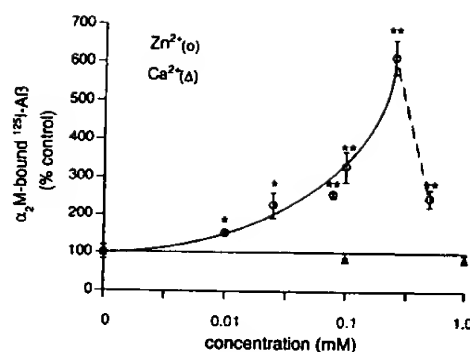


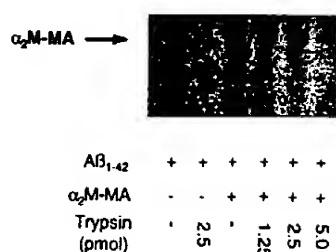
FIG. 5. Effects of  $\text{Zn}^{2+}$  and  $\text{Ca}^{2+}$  on the binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M-MA}$ .  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  (5 ng/ml) was incubated with  $\alpha_2\text{M-MA}$  (1 mg/ml) in 100 mM Tris-HCl buffer (pH 8.0) at  $37^\circ\text{C}$  for 2 h in the presence of various concentrations of  $\text{Ca}^{2+}$  or  $\text{Zn}^{2+}$ . Bound  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  was immunoprecipitated and the radioactivity determined as described in the text. Note that low concentrations of  $\text{Zn}^{2+}$  increase  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  binding to  $\alpha_2\text{M-MA}$ , whereas high concentrations directly precipitate  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  or  $\alpha_2\text{M-MA}$ , resulting in a less immunoprecipitable  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}/\alpha_2\text{M-MA}$  complex. \* $p < 0.05$ ; \*\* $p < 0.01$ , by Student's  $t$  test.

may affect the binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$ , we examined the effects of pH and the cations  $\text{Ca}^{2+}$  and  $\text{Zn}^{2+}$  on the binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$  by using the immunoprecipitation method. The binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M-MA}$  was found to be dependent on pH. The binding complex being relatively stable over the pH range examined (5.0–8.0, data not shown), however, the absolute amount of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  bound to  $\alpha_2\text{M-MA}$  increases by  $\sim 60\%$  as the pH is decreased from 7.5 to 5.0. This finding was confirmed by using native gel electrophoresis to separate bound from free ligand (data not shown).

Previous studies have shown that both  $\alpha_2\text{M}$  and  $\text{A}\beta$  can bind  $\text{Zn}^{2+}$  (Parisi and Vallee, 1970; Bush et al., 1994), and we therefore examined whether the formation of the  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}/\alpha_2\text{M}$  complex is influenced by  $\text{Zn}^{2+}$ . In the presence of  $\text{Zn}^{2+}$  (0.01–0.25 mM) the binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M-MA}$  is increased in a concentration-dependent fashion (Fig. 5). At low  $[\text{Zn}^{2+}]$  (i.e.,  $\leq 0.25$  mM), we observed enhanced binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$ , whereas higher  $\text{Zn}^{2+}$  concentrations ( $> 0.25$  mM) resulted in a direct precipitation of the  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$ , yielding lower amounts of immunoprecipitable complex (Fig. 5). By contrast,  $\text{Ca}^{2+}$  concentrations of  $\leq 1$  mM had no effect on the binding of  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  to  $\alpha_2\text{M}$  (Fig. 5).

Because the binding of IL-2 to  $\alpha_2\text{M-MA}$  has been shown to protect this peptide substrate from exogenous proteinases (Legrés et al., 1995), we subjected the  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}/\alpha_2\text{M-MA}$  complex to treatment with various concentrations of trypsin. Both gel and immunoprecipitation studies revealed that  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  resisted trypsin digestion when bound to  $\alpha_2\text{M-MA}$  (Fig. 6). By contrast, unbound  $^{125}\text{I}$ - $\text{A}\beta_{(1-42)}$  was readily degraded by trypsin.

We have also examined whether the plaque-associ-



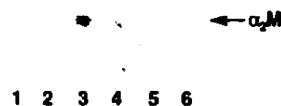
**FIG. 6.** Effect of trypsin on  $^{125}$ I- $A\beta_{(1-42)}$  bound to  $\alpha_2$ M-MA. Preincubation of  $^{125}$ I- $A\beta_{(1-42)}$  (5 ng/ml) with  $\alpha_2$ M-MA (1 mg/ml) protects the peptide from subsequent proteolysis by trypsin. The autoradiogram shows that complexes of  $^{125}$ I- $A\beta_{(1-42)}$  with  $\alpha_2$ M or  $\alpha_2$ M-MA resist digestion by 1.25, 2.50, and 5.0 pmol of trypsin.

ated protein  $\alpha_1$ -antichymotrypsin affects the formation of the  $^{125}$ I- $A\beta_{(1-42)}/\alpha_2$ M complex. In these experiments, various amounts of  $\alpha_1$ -antichymotrypsin were added to the binding reaction before equilibrium. Unexpectedly, with increasing concentrations of  $\alpha_1$ -antichymotrypsin, the amount of  $^{125}$ I- $A\beta_{(1-42)}/\alpha_2$ M complex decreased dramatically (Fig. 7), suggesting that  $\alpha_1$ -antichymotrypsin is able to inhibit the binding of  $^{125}$ I- $A\beta_{(1-42)}$  to  $\alpha_2$ M.

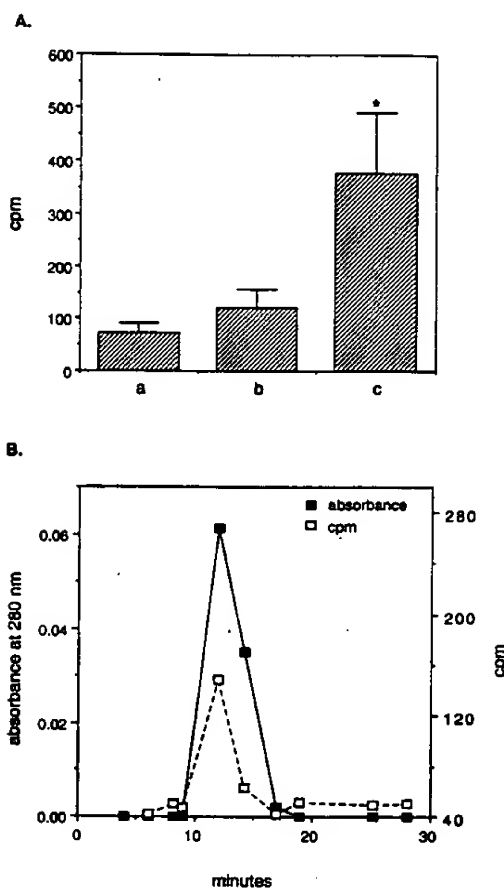
Finally, to determine whether  $A\beta_{(1-42)}$  can bind to  $\alpha_2$ M present in serum, we incubated human serum with  $^{125}$ I- $A\beta_{(1-42)}$  (2 h, 37°C) and attempted to immunoprecipitate or separate the  $^{125}$ I- $A\beta_{(1-42)}/\alpha_2$ M complex by using anti- $\alpha_2$ M antiserum or HPLC. From Fig. 8, it is apparent that after incubation of human serum with  $^{125}$ I- $A\beta_{(1-42)}$ , immunoprecipitation of  $\alpha_2$ M with anti- $\alpha_2$ M antiserum (A) or separation of  $\alpha_2$ M by using HPLC (B) reveals binding of  $^{125}$ I- $A\beta_{(1-42)}$  to  $\alpha_2$ M present in serum. These data demonstrate that in the presence of other serum proteins  $^{125}$ I- $A\beta_{(1-42)}$  can bind to  $\alpha_2$ M.

## DISCUSSION

$A\beta$ , the main component of neuritic plaques, which are characteristic features of AD neuropathology, is also present as a normal constituent of biological fluids and is apparently produced by many cells during normal cellular metabolism (Selkoe, 1994). The concen-



**FIG. 7.** Effects of  $\alpha_1$ -antichymotrypsin on the binding of  $^{125}$ I- $A\beta_{(1-42)}$  to  $\alpha_2$ M. In lanes 1 and 2, 0.2 ng  $^{125}$ I- $A\beta_{(1-42)}$  was incubated with 0 and 20  $\mu$ g  $\alpha_1$ -antichymotrypsin only. In lanes 3, 4, 5, and 6, which represent binding reactions (40  $\mu$ l) with 0, 5, 10, and 20  $\mu$ g  $\alpha_1$ -antichymotrypsin, respectively,  $\alpha_1$ -antichymotrypsin was added to binding reactions consisting of 0.2 ng  $^{125}$ I- $A\beta_{(1-42)}$  and 40  $\mu$ g  $\alpha_2$ M. With increasing amounts of  $\alpha_1$ -antichymotrypsin (0, 5, 10, and 20  $\mu$ g), the binding of  $^{125}$ I- $A\beta_{(1-42)}$  to  $\alpha_2$ M decreased, as revealed by the autoradiogram.



**FIG. 8.** Binding of  $^{125}$ I- $A\beta_{(1-42)}$  to  $\alpha_2$ M present in human serum. **A:**  $^{125}$ I- $A\beta_{(1-42)}$  (50 ng/ml) was incubated with human serum (100  $\mu$ l) at 37°C for 2 h. Immunoprecipitation of the  $^{125}$ I- $A\beta_{(1-42)}/\alpha_2$ M complex from human serum with anti- $\alpha_2$ M antiserum. Column a,  $^{125}$ I- $A\beta_{(1-42)}$  and human serum; column b,  $^{125}$ I- $A\beta_{(1-42)}$ , human serum, and anti-human IgG antibody; and column c,  $^{125}$ I- $A\beta_{(1-42)}$ , human serum, and anti-human  $\alpha_2$ M antiserum.  $p < 0.05$ , by Student's  $t$  test. **B:**  $^{125}$ I- $A\beta_{(1-42)}$  (50 ng/ml) was incubated with human serum (100  $\mu$ l) at 37°C for 2 h. The sample was analyzed by HPLC as described in Materials and Methods. The resulting  $\alpha_2$ M-containing fractions were associated with  $^{125}$ I- $A\beta_{(1-42)}$ .

tration of  $A\beta$  in biological fluids such as CSF is  $\sim 10^{-9}$  M (Haass et al., 1992). Given that the circulating or brain concentrations of  $A\beta$  are different in the patients who subsequently develop AD, factors that determine or affect the catabolism or clearance of  $A\beta$  (or both) may contribute to  $A\beta$  aggregation and deposition into either diffuse (preamyloid) and (or) neuritic (senile) plaques in brain (Van Gool et al., 1993; Selkoe, 1994; Tabaton et al., 1994; Kuo et al., 1996). In the present study, we have found that the major circulating pan-proteinase inhibitor  $\alpha_2$ M is capable of binding  $^{125}$ I- $A\beta_{(1-42)}$  with an apparent dissociation constant of  $\sim 3.8 \times 10^{-10}$  M and, therefore, may bind or sequester  $A\beta$  at the low concentrations of this peptide(s) that occur physiologically. Moreover, the binding of  $^{125}$ I- $A\beta_{(1-42)}$  to  $\alpha_2$ M appears to be relatively specific in that binding can be inhibited by coincubation with na-



nomolar concentrations of  $A\beta_{(1-42)}$  or  $A\beta_{(1-40)}$  but not by the reverse peptide  $A\beta_{(40-1)}$  or by cytokines IL-1 $\beta$  and IL-2. Both IL-1 $\beta$  and IL-2 have been previously shown to bind with relatively high affinity to  $\alpha_2M$  (Borth and Luger, 1989; Legr s et al., 1995). These data also confirm that the noniodinated  $A\beta_{(1-40)}$  or  $A\beta_{(1-42)}$  peptides can effectively compete with  $^{125}I$ - $A\beta_{(1-42)}$  in binding to  $\alpha_2M$  and, therefore, the ability of  $A\beta$  to bind to  $\alpha_2M$  does not appear to be due to peptide iodination.

The binding of  $^{125}I$ - $A\beta_{(1-42)}$  to  $\alpha_2M$  does not appear to require proteolytic activation of  $\alpha_2M$ , because both native  $\alpha_2M$  and  $\alpha_2M$ -MA bind  $^{125}I$ - $A\beta_{(1-42)}$  (Fig. 1C). These findings are reminiscent of those recently reported by Legr s and colleagues (1995) who demonstrated similar high affinity binding of  $^{125}I$ -recombinant human IL-2 to native and  $\alpha_2M$ -MA. By contrast, only activated  $\alpha_2M$  is capable of binding to IL-1 $\beta$  (Borth and Luger, 1989).

Because both  $\alpha_2M$  and  $A\beta$  have been reported to bind  $Zn^{2+}$ , we examined the effects of  $Zn^{2+}$  on  $^{125}I$ - $A\beta_{(1-42)}$  binding to  $\alpha_2M$ . Relatively low concentrations of  $Zn^{2+}$  (0.01–0.25 mM) enhance the binding of  $^{125}I$ - $A\beta_{(1-42)}$  to  $\alpha_2M$ , whereas higher concentrations (>0.25 mM) directly precipitate the  $^{125}I$ - $A\beta_{(1-42)}$  from solution (data not shown). By contrast,  $[Ca^{2+}]$  of  $\leq 1$  mM fails to alter the binding of  $^{125}I$ - $A\beta_{(1-42)}$  to  $\alpha_2M$  (Fig. 6). Although the postulated role of  $Zn^{2+}$  in the pathogenesis of AD is controversial (Lui et al., 1990), our data suggest that low physiologically relevant  $[Zn^{2+}]$  may facilitate the formation of the  $A\beta/\alpha_2M$  complex. The latter may facilitate  $A\beta$  deposition into plaques containing  $\alpha_2M$  (see below).

It is interesting that similar to the cytokine IL-2, the binding of  $^{125}I$ - $A\beta_{(1-42)}$  to  $\alpha_2M$  protects the peptide from proteolysis by exogenous trypsin (Fig. 6). It was postulated that the trypsin-sensitive sites on the peptide became inaccessible after binding to  $\alpha_2M$ -MA. We have found that  $\alpha_1$ -antichymotrypsin (another plaque-associated protein) (Abraham et al., 1988) also blocks the proteolysis of  $A\beta$  by  $\alpha_2M$ -T (Zhang et al., 1996). Curiously, in addition to inhibiting  $\alpha_2M$ -T-induced catabolism of  $A\beta$ ,  $\alpha_1$ -antichymotrypsin inhibits the binding of  $^{125}I$ - $A\beta_{(1-42)}$  to  $\alpha_2M$  (Fig. 7). It is possible that the previously reported properties of  $\alpha_1$ -antichymotrypsin to bind to  $A\beta$  may reduce the binding of  $^{125}I$ - $A\beta_{(1-42)}$  to  $\alpha_2M$  (Fraser et al., 1993). Finally,  $^{125}I$ - $A\beta_{(1-42)}$  binding to  $\alpha_2M$  can also be demonstrated after incubation of  $^{125}I$ - $A\beta_{(1-42)}$  with human serum in vitro, and thus, the binding of  $^{125}I$ - $A\beta_{(1-42)}$  to  $\alpha_2M$  occurs in the presence of other plasma proteins (Fig. 8). Although it is possible (perhaps likely) that other plasma proteins will bind  $A\beta$ , these experiments, in our view, demonstrate the  $A\beta$  binding capacity of  $\alpha_2M$ , even in the presence of other potential competing binding proteins or catabolic enzymes. In addition, we have not addressed the possibility that iodination of  $A\beta$  may interfere with the conformation of this peptide and its binding ability (Bush et al., 1994). Further

studies using more conservative labeling methods are under way.

What, if any, is the physiological or pathophysiological significance of the binding of  $A\beta$  to  $\alpha_2M$ ? How could such binding be relevant (if at all) to the pathogenesis of AD? At present, we can only speculate on the possible significance of  $A\beta$  binding to  $\alpha_2M$ . Because  $A\beta$  is normally produced by many cell types and because native  $\alpha_2M$  can bind (with high affinity) the relatively low concentrations of circulating or tissue  $A\beta$ , it is likely that under normal (physiological) conditions native  $\alpha_2M$  can sequester or bind  $A\beta$ . Conceivably, after activation of  $\alpha_2M$  by proteinases, the associated (and protected)  $A\beta$  would be "cleared" via the  $Ca^{2+}$ -dependent binding and endocytosis of the  $A\beta/\alpha_2M$  complex, i.e., by the  $\alpha_2M$ /LRP. Thus, the binding of  $A\beta/\alpha_2M$  to the LRP could serve to remove or clear  $A\beta$  from tissues, especially the brain, which expresses relatively high amounts of LRP (Tooyama et al., 1993). Alternatively, such binding and subsequent LRP-mediated endocytosis of the  $A\beta/\alpha_2M$  complex by neurons (as opposed to macrophages) could result in enhanced deposition, especially if  $A\beta$  catabolism or binding to  $\alpha_2M$  is inhibited by endogenous inhibitors such as  $\alpha_1$ -antichymotrypsin. It is significant that  $\alpha_1$ -antichymotrypsin has been reported to be present in amyloid-containing plaques and is expressed by astrocytes in affected (but not unaffected) areas of AD brain (Das and Potter, 1995). Thus,  $\alpha_2M$  may serve to protect  $A\beta$  from proteolytic degradation and contribute to its deposition in plaques. Finally, it is also possible that the clearance of the  $A\beta/\alpha_2M$  complex is affected by other LRP ligands, especially apolipoprotein E (Van Gool et al., 1995). An isoform-specific competition by apolipoprotein E-containing chylomicrons could further facilitate  $A\beta$  deposition and contribute to the pathogenesis of AD. The latter may contribute to the earlier onset of AD in individuals with either one or two copies of the apolipoprotein E4 allele (Strittmatter and Roses, 1995). These hypotheses are currently being investigated.

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